Migrant steelhead passage after dam removal, river reroute, and channel evolution in the Carmel River, California

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Summary

The dam removal and reroute of Carmel River at San Clemente created a steep channel with a series of engineered step pools through the old reservoir sediments just upstream of the old dam site. High flows in January and February of 2017 substantially re-organized this reroute into a braided channel with self-formed step pools. One of the primary purposes of the dam removal was to provide improved upstream passage for migratory steelhead, a threatened species native to the river. To test whether the reorganized channel provided improved passage to steelhead, we tagged migratory adults entering the river in 2021 and 2022, and tracked their upstream progress through a series of tag reader sites below and above the reroute. Fish moved readily through the reroute segment, and were inferred to spawn both above and below the reroute proportionally to available habitat. Ease of passage appeared to be slightly improved relative to the historical fish ladder on the now-removed dam. Net upstream velocity of migrants through the section of river with the reroute was substantially slower than in downstream sections of river, probably due a mixture of generally steeper channel conditions throughout this canyon section of river, and challenges posed specifically by the reroute. Relative to faster migration speeds in the gentler channel gradients of Carmel Valley, the additional time required for steelhead to move through this steeper canyon section had a median of 2.7 days. Some of this difference may be due to the reroute, but even so the ease of passage appears to have been improved by the removal of the dam.

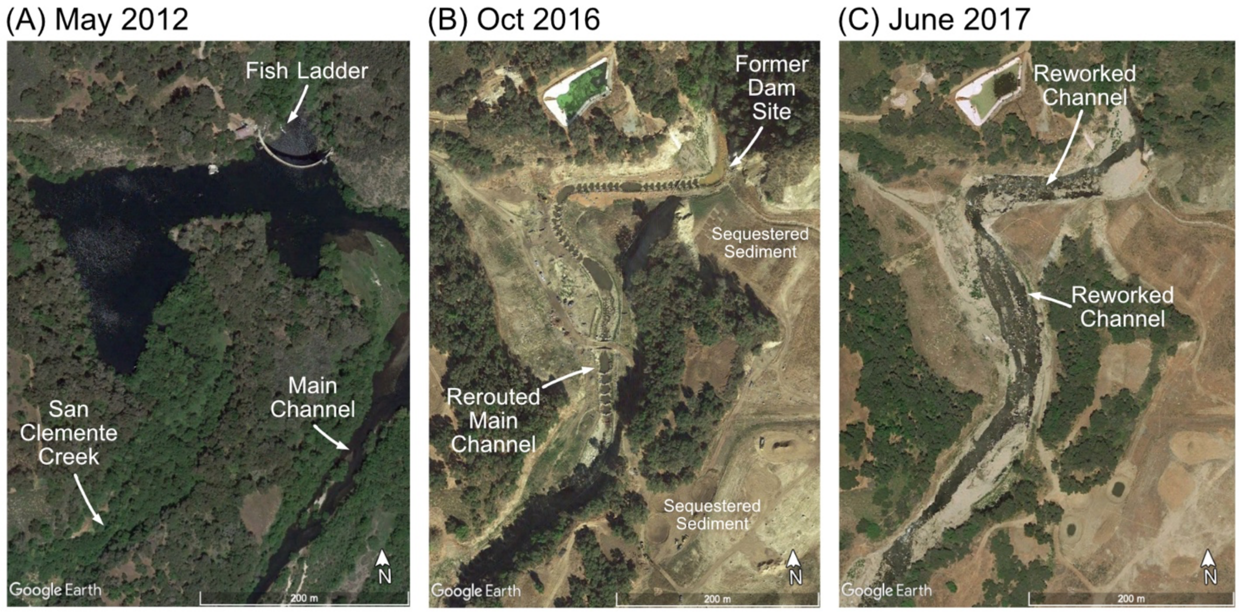

Figure 1. The Carmel River reroute through time. (A) San Clemente Dam and the remnant portion of the reservoir (not filled with sediment) in May 2012. The bottom end of the fish ladder is visible entering the plunge pool just downstream of the dam. (B) The rerouted main channel one year after construction, showing constructed step pools. The notch in the ridge, rerouting the main channel into the old course of San Clemente Creek, is just outside the bottom left corner of the image. (C) The re-organized braided channel after the wet season of 2017, which included one 20-year flow event and two 10-year flow events. Images from Google Earth.

Introduction

The removal of San Clemente Dam from the Carmel River in 2015 eliminated an important seismic hazard and restored habitat-forming processes to downstream reaches of the Carmel River, creating a variety of ecological benefits (Harrison et al. 2018). By the time of the dam's removal, its reservoir was largely useless due to decades of sediment accumulation, which had shrunk the original water storage capacity by 90%. The key design challenge for the dam removal was arguably not the dam itself, but the fate of all this sediment. One option was simply to allow the river itself to transport the sediment downstream, as in other western dam removals, but this posed unacceptable flooding hazards to downstream residential communities. Another option was to truck the sediment out, but this would have required ~250,000 round trips of dump trucks over local roads, also considered unacceptable and perhaps infeasible. In the end, a particular feature of the site allowed a third option to be pursued: sequestering the vast majority of sediment in place at the old reservoir site.

The feature of the site that enabled sequestering was San Clemente Creek. The creek originally joined Carmel River adjacent to the location chosen a century ago for dam construction, and its upstream course paralleled the main river channel for ~0.8 km before veering westward. In 2015 prior to dam removal, a notch was cut through the small ridge separating the two channels, allowing the Carmel River to be rerouted through the old creek valley and around the vast majority of reservoir sediment (Figure 1). Reservoir sediment in the reroute was partially removed and then graded to create a new river channel, as steep as 5% in some portions; large boulders were trucked in and positioned to create a series of engineered step pools (Figure 1B); and the sequestered sediment in the rest of the old reservoir to the east was revegetated and stabilized with native plant species.

An important intent of the dam removal was to improve upstream passage for migratory steelhead (*Oncorhynchus mykiss*), a threatened fish species with an anadromous life-history that matures in the Pacific Ocean but migrates up local rivers and creeks to reproduce during annual spawning runs. The old San Clemente Dam had a fish ladder (Figure 1A) that was actively used by steelhead, but its out-dated design and steep climb were nonetheless believed to impede fish passage. The engineered step pools in the reroute were designed to mimic the jumps and pools typically encountered by steelhead in natural habitats, and also to be geomorphologically active over the long term, mimicking the form and function of step-pools that naturally self-form in high-gradient channels of mountain streams (Montgomery and Buffington 1997). And active they proved to be, when a series of high-flow events in the exceptionally wet year of 2017 completely reorganized the channel, only two years after its construction (Figure 1C). The new configuration has largely persisted to the time of this writing (summer 2022), including through another wet year in 2019 and a series of large atmospheric river storms in late 2021, as bankside vegetation has developed and apparently stabilized the channel.

Although the loss of the constructed step pools might be viewed as a failure of the reroute project design, arguably this engineered section of river has behaved exactly as we should expect it to behave, and in so doing generated a quasi-natural channel morphology. The key question addressed here is: what are the implications for steelhead passage? We address this question by tagging migrant steelhead and tracking their upstream progress through the river and its reroute.

Table 1. Tagging and reader sites in the passage study.

River km	Role	Station ID	Description
1.12	Fish tagging	Weir	Resistance-board weir just above estuary.
4.36	Tag reader	RC	Rancho Canada monitoring site (MPRPD)
5.81	Tag reader	RSC	Rancho San Carlos monitoring site (Cal Am).
14.61	Tag reader	SCAR	Scarlett monitoring site (Cal Am).
25.90	Ecotone	-	Transition from alluvial valley to canyon
28.61	Tag reader	SH	Sleepy Hollow bridge
30.42	Counting station (before only)	Reroute	Before: San Clemente Fish Ladder After: Downstream end of reroute
31.28	Notch	-	Upstream end of reroute
40.97	Tag reader	BLP	Below-Los-Padres reader site
41.21	Tag reader & Counting station	LP	Ladder trap and adjacent spillway of Los Padres Dam. Tag reader operated in 2022 only.

Methods

To assess upstream passage of steelhead through the reroute, in 2021 and 2022 we captured adult steelhead as they swam up from the estuary of Carmel River, tagged and released them, and then tracked their upstream progress via a series of tag readers distributed along the river corridor up to a second, extant dam about 10 km above the reroute site and 40 km above the tagging site (Table 1). This second dam, Los Padres Dam, has a fish ladder leading into a trap, from which adult steelhead are removed daily by the dam operator, and transported to the reservoir for release upstream. Daily counts of migrant steelhead have been recorded for decades at this trap, and also at the fish ladder of San Clemente Dam prior to its removal in 2015, which we use as background information on passage before dam removal. As migrant steelhead ascend the river, they travel through a low-gradient alluvial river valley up to about river km 26, where they enter a steeper V-shaped canyon that persists all the way to the upper reservoir. Redd surveys collected over the last few decades (Monterey Peninsula Water Management District, Unpublished data) indicate that spawning activity is evenly dispersed throughout these reaches, except in the lowest reaches of the alluvial portion of the river (< 12 rkm), which tend to dry up each summer and which receive fewer redds.

Adult migrant steelhead were captured daily during the migration season (Jan – May), using a resistance-board weir just up from the physical transition of estuary to river channel. Each morning, captured fish were removed from the trap on the weir, implanted with PIT tags in the dorsal sinus area (23mm, half-duplex, ISO 11784/11785 compliant), allowed to recover and then released immediately upstream of the weir. We used six PIT tag antennas located throughout the mainstem to monitor fish movements (Table 1). The PIT tag antennas were a flexible-pass-through design (Ohms et al. 2023) and had high detection rates for 23-mm PIT tags (Ohms et al. 2022). Unfortunately, the difficulty of access to the canyon upstream of the reroute in winter prevented us from establishing an additional monitoring station at the top of the reroute, which would have improved the spatial resolution of adult movement in the reroute versus the upstream canyon section. At the same time, there was no available pre-removal data for passage delays at this spatial resolution so before-after comparisons are necessarily limited to adults counted at the trap further upstream at Los Padres Reservoir.

We compiled the resulting data into discrete "moves," defined as consecutive pairs of detections of a particular tagged fish. Each move was then categorized as an upstream, downstream, or stationary move, the latter being two consecutive detections at the same reader site. The data were used to address two questions:

1. What is the distribution of spawning activity above and below the reroute, and has it changed since the dam removal?
2. Do migrants move more slowly through the reroute site, versus other portions of the migration corridor?

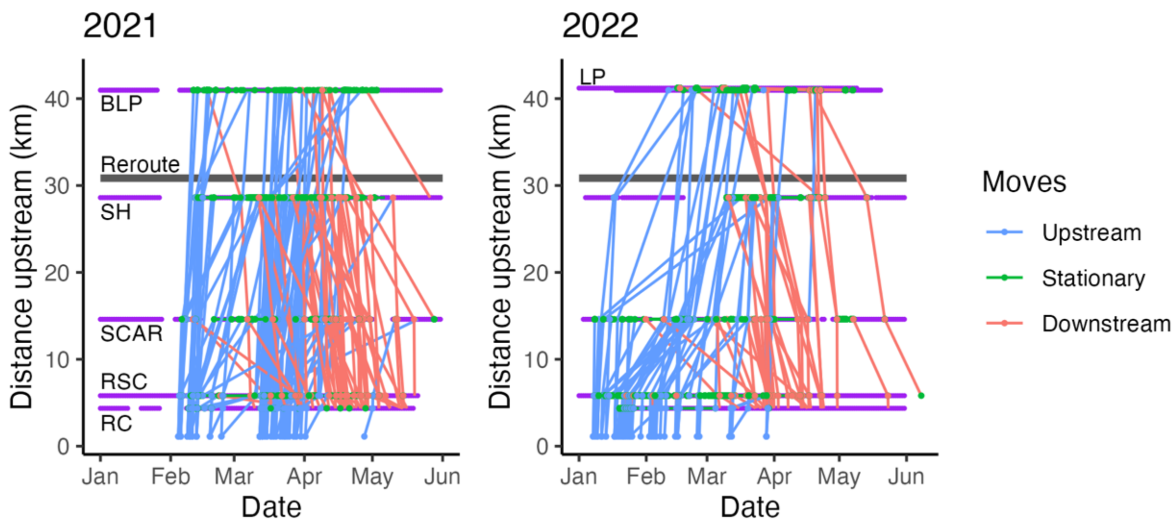

Figure 2. Detected moves of adult migrant steelhead captured and tagged at the weir (Distance upstream = 1.1 km), for the 2021 and 2022 migration seasons. The horizontal gray bar marks the location of the reroute channel upstream of the SH tag reader. Purple bars mark days in which reader sites were operational; gaps were created when ambient EF noise or floating debris temporarily disabled monitoring stations.

Results

We tagged a total of 104 and 61 migrants in 2021 and 2022, respectively, and subsequently detected 95% of these fish passing one or more upstream reader sites. A plot of moves (Figure 2) shows that most fish moved quickly upstream, although some tarried for days or weeks, especially between readers RC and SCAR in 2022. The latter was likely due to low flows in the 2022 season, which had very little rain during the peak migration season of February and March.

Many of the tagged fish were subsequently detected moving back downstream, presumably back to the ocean after spawning, although some moves may also be shed tags or spawner carcasses washing downstream with the current. Figure 2 shows no obvious difference in movement patterns for the reroute segment (SH-BLP) versus other river segments.

<u>Distribution of spawning activity</u>

For each tagged migrant adult, we identified the upper-most reader station at which it was detected, and inferred that it likely spawned in the river segment between this station and the next station upstream. We expected that the proportion of fish spawning in each segment would roughly match the proportion of river kilometers available in each segment, and Figure 3A shows that this was approximately true in both years. If the reroute somehow impeded migration, the data for inferred spawning activity above the reroute should consistently fall below the 1:1 line in Figure 3A, but this was not the case. Fish spawned above the reroute in rough proportion to the available habitat, and we see no evidence of impeded passage.

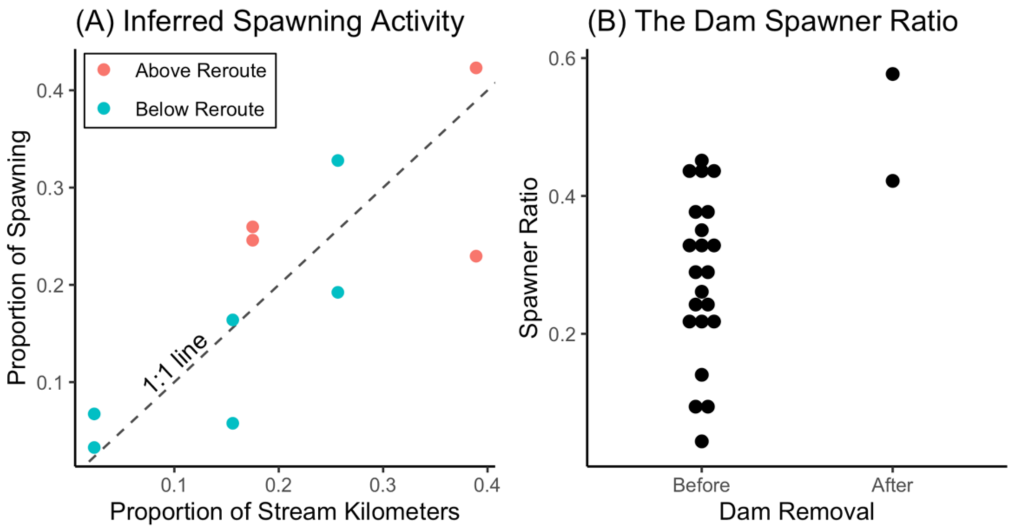

Figure 3. (A) Comparison of inferred spawning activity in river segments above and below the reroute in each of two years of tagging (2021-2022). Two segments were above the reroute: the headwaters upstream of LP/BLP, and the canyon reach between BLP and SH (see Table 1); only 85% of the latter segment was above old dam site. Three segments were below the reroute: RC to RSC, RSC to SCAR, and SCAR to SH (see Table 1). (B) The dam spawning ratio before and after the dam removal. The before period covered 1992-2013, but omitted 2014-2015 due to zero counts at one or more of the dams. The after period is 2021-2022.

Has the distribution of spawning activity changed since the dam removal? Before removal, migrant spawners were counted at both dams and their ratio indicates the proportion of fish passing San Clemente Dam that also reached Los Padres Dam. Figure 3B shows that this spawner ratio could vary substantially from year to year, but always stayed below 0.5 in the 22 years before dam removal that had at least one adult passed at each dam. For comparison, we computed two years of spawner ratios after dam removal, using fish detected at SH versus BLP/LP (Figure 3B, right). These two datapoints appear slightly more favorable, suggesting improved passage.

To test for this improvement more formally, we fit a logistic regression in which each adult was considered an independent trial. Besides the fixed effect of dam removal, the regression included year as a random effect to account for influences on behavior shared across across fish in a given year due to environmental factors such as flow, weather conditions, water quality and the like. We also included an offset (covariate with regression coefficient assumed to equal 1.0), to account for the fact that reader site SH is slightly downstream of the counting station at the old dam site. Based on a tally of accessible channel kilometers in the stream network, the habitat above site SH is likely to receive 3.36% more spawning activity than the habitat above the old dam site, and the offset accounts for this slight discrepancy between the data for the before and after period. The 3.36% was transformed to log-odds to be consistent with the linear predictor of the logistic regression and incorporated as an offset. Years with higher run size also tended to have higher spawner ratios for some reason (data not shown), so we included ranked run size (from Los Padres counts) as a covariate to improve statistical power.

The hypothesis that dam removal did not change spawner ratio was rejected at $p = 0.016$. This is fairly clear evidence that the passage situation was improved by dam removal and river reroute, despite only two years of data for the "After" period.

<u>Are migrants slowed down by the reroute?</u>

For upstream moves, the net upstream velocity through Carmel Valley and the lower canyon tended to be substantially faster than through the upper canyon and reroute segment (Figure 4). Indeed, median velocity in the upper canyon and reroute segment was significantly slower (p = 0.009, two-sample Brown-Mood median test), only 0.10 km/hr, versus 0.21 km/hr for segments downstream of reader site SH. Strictly speaking, it is not clear if this difference is due to the reroute specifically, or due to the generally steeper channel gradients in the upper canyon. If we make the strong assumption that the reroute causes all the difference in median speed, then additional time required to traverse it is 66 hrs, or 2.7 days, during upstream migration. Much more likely, in our view, is that the slower speed is a mixture of delay associated with the steepest, roughest part of the reroute, and generally slow upstream progress in the canyon relative to the low-gradient alluvial channel closer to the ocean.

Figure 4. Net upstream migration speed of adults during upstream moves, for moves between reader sites downstream of Sleepy Hollow (Below SH), and for moves in the reroute segment (between Sleepy Hollow and the reader site just downstream of Los Padres Dam).

Conclusions

Relative to faster migration speeds in the gentler channel gradients of Carmel Valley, the median of additional time spent by steelhead in the steeper canyon section was about 2.7 days. Some of this difference may be due to the reroute, but some or most is also likely due to the generally steeper channel conditions in the canyon. Overall, ease of passage by adult steelhead appears to have been improved by the replacement of the historical fish ladder with the reroute channel, as judged by the distribution of spawning activity before and after dam removal.

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